Kinetic Physics in ICF Workshop: Discussion session – Day 3 – Theory

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Thursday, April 7, 1:30 pm
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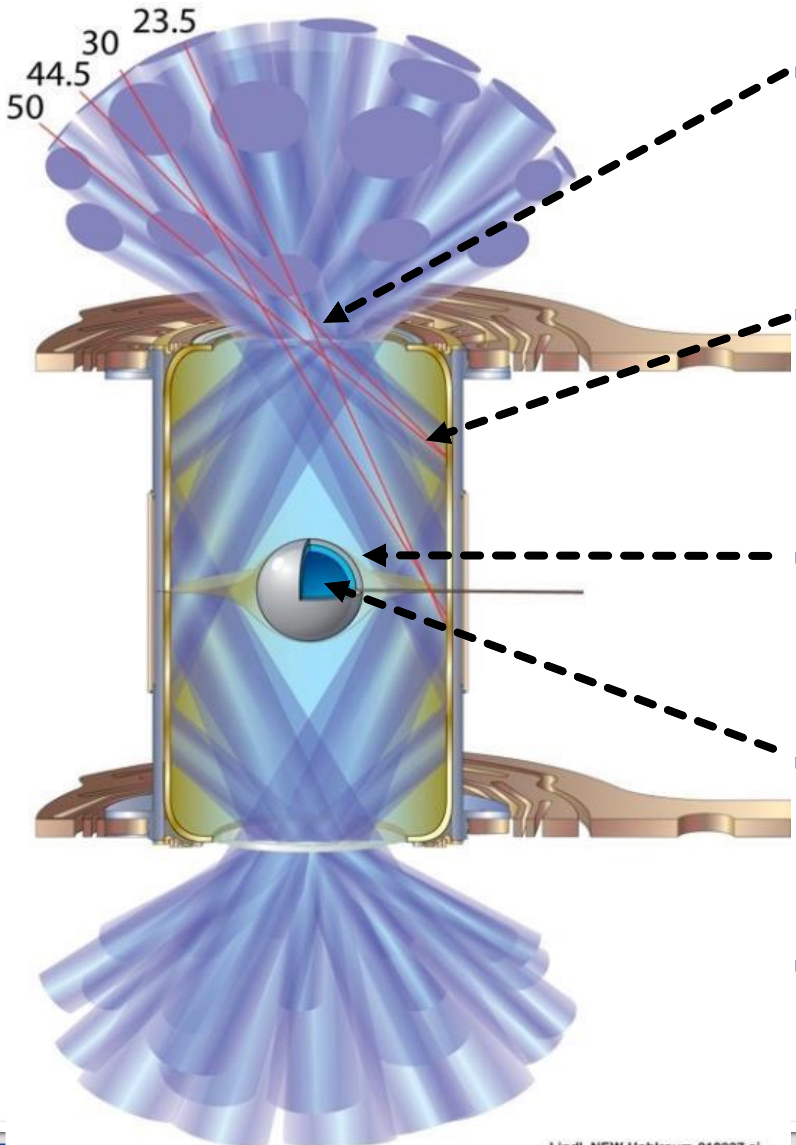
Likely regions in ICF where kinetic physics may be important based on today's talks:



- **LEH and laser/gas interactions**

1.	*Afeyan*	*Hot electron generation, refluxing*

- **Hohlraum gas/wall interface**

1.	*Afeyan*	*Hot electron generation, refluxing*
2.	*Simakov*	*Interpenetration in stagnation*

- **Ablator**

1.	*Sunahara*	*Nonlocal e-xport*
2.	*Orth*	*Spallation?*

- **Shock dynamics, hot spot assembly, burn**

1.	*R. Mason*	*Viscosity in shock front*
2.	*E. Vold*	*Viscosity*
3.	*Olson*	*Wetted foams*
4.	*Cohen*	*KL physics*

- **Other**

Questions to guide discussion:

1. **Importance:** How would this phenomenon impact the overall performance of an ICF implosion?
   - How would it impact observables?
   - What back-of-the-envelope calculation or test simulation supports the proposed impact(s)?

2. **Next Steps:** What proposed experiment or test problem would clearly demonstrate or benchmark this effect?

1. Quick overview of today's presentations on "Theory"

- **How important are these effects to ignition?**

Landen: Evidence file ac ross NIF platforms and gauging of kinetic roles

Mason: Real viscosity diffuses shock front, but how is ignition margin affected? Flux limit sensitivity to multiple cells? Testable? Rosenberg EP's already? Other viscosity models? Why is B 2x larger with viscosity despite smoothing?

Vold: xRage applied to pair of Omega shots shows qualitative agreement and consistent with Ho/Zimmerman results. Less convergence from viscosity => less Pstag?

Sunahara: Spark experiment shows interpenetrating flows; modeling in progress with DSMC Langevin model. Nonlocal xport important for DD. Is time-dependent flux multiplier needed in ID?

Afeyan: Exploit LPI to understand kinetics, measure space and time varying hots, measure vdf's.

Simakov: Plasma rad-hydro transport model includes O(Kn) effects. Same physics as in xRage? Impact on ignition margins?

Cohen: Kinetics matter, but KL tail effect on fusion reaction rate is small.

Kagan: Simple kinetics model might explain DD vs DT Ti anomaly using local Kn from hot-spot boundary perturbations. Extended kTi from tenuous plasma to strong coupling regime.

1. Quick overview of today's presentations on "Theory"

- **How important are these effects to ignition?**

Olson: Wetted foam+fuel platform can span Kn's for kinetic to fluid-like regime!
Orth: Delay in phase transition behind first shock may seed RT/RM at fuel/pusher interface (scale size?); testable on Omega/NIF? Role for MD simulations to constrain phase transition time scale? Vary grain size in 1D slab experiments on OMEGA?

Electron and ion thermo-diffusion may be greatly enhanced in high-Z hohlraums filled with low-Z gas

HOHLRAUM DIFFUSION

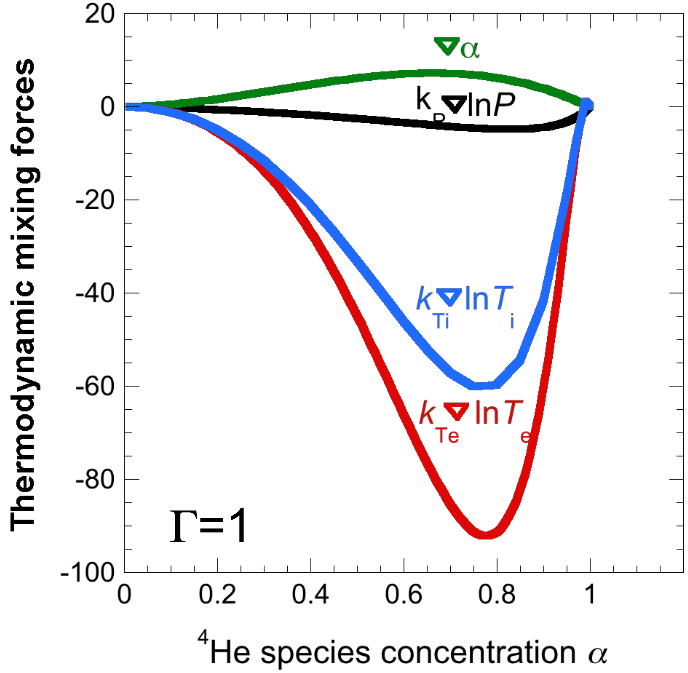
?

$$i = -\rho D \cdot (\nabla\alpha + k_P \nabla \ln P + k_{T_e} \nabla \ln T_e + k_{T_i} \nabla \ln T_i + k_\nu \nabla^2 \upsilon$$

Kagan and Tang, Phys. Lett. **A 378**, 1531 (2014)

$$\nabla \ln T = \nabla \ln P\left(\frac{\gamma - 1}{\gamma}\right) + \frac{\Delta Z}{\bar{Z} + \Gamma^{-1}} \frac{m_1}{m_2} \times \frac{\nabla\alpha}{[\alpha + (1-\alpha)m_1/m_2]^2},$$

Amendt, Bellei and Wilks, PRL **109**, 075002 (2012)



- Large ΔZ can promote temperature inversion within mix layer, potentially leading to throttled e$^-$ transport and reduced drive

- Local approximation for T,P profiles does not apply to strong shocks

THEORY RESULTS SUMMARY

- Real viscosity in simulations shows deviations from inviscid results
- Self-consistent inclusion of plasma transport in fluid models may help to understand heating/stagnation phenomena in hohlraums/capsules
- Phase transition delay in strong shocks in ablator may eject material from ablator into ice
- Wetted foam platform on the NIF provides knob on Kn through gas density
- Variable convergence Symcaps with hydro-equivalent DD, D3He fill could provide another Kn platform: Does Rygg anomaly exist on the NIF?
- Hot electron anisotropy could seed non-uniform burn
- Global KL physics doesn't appear to greatly affect burn, but locally large Kn pockets from instability may have important effect
- Resistive heating from time-varying (converging) shock in gaseous fuel?
- Does enthalpy of mix contribute to low DSR's?

THEORY ACTION ITEMS

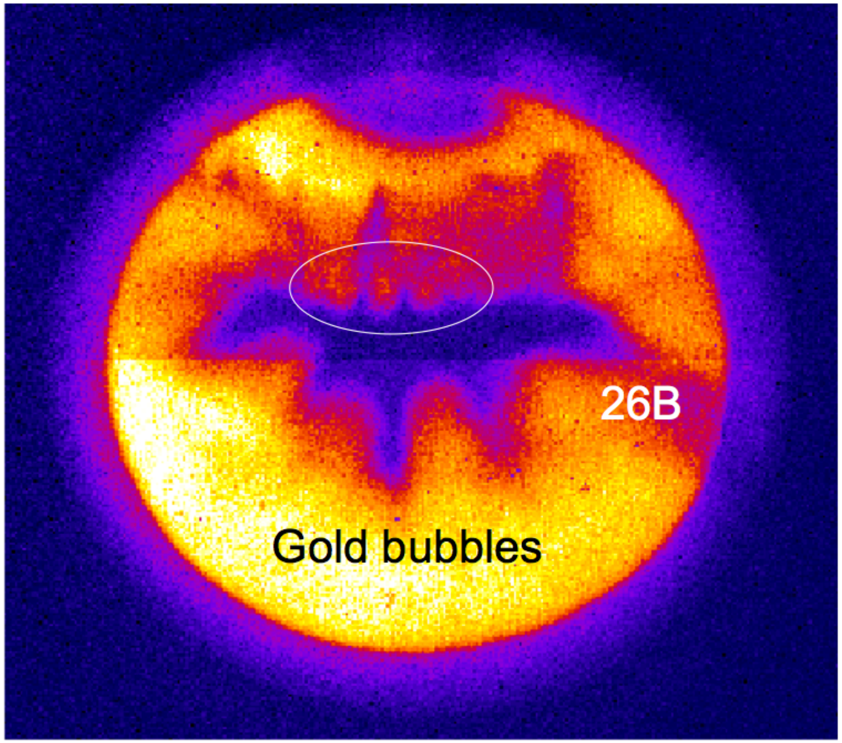
- Quantitatively assess impact of viscosity on ignition: devise test of simulations
- Understand limits of mass diffusive flux expression especially for strong shocks
    - Impact on energy transport
- Spallation from 1st shock in solid ablator: Design Omega experiment to test
- Design Hy-Eq Symcap platform to dial in kinetic effects
- Hot electron anisotropy could seed non-uniform burn: Quantify
- Assess upper bound on possible resistive heating in fuel
- Does enthalpy of mix contribute to low DSR?
- Hohlraum/gas interface mix from ion diffusion or hydro-instability: does it play a role on missing energy / multipliers?

THEORY ACTION ITEMS

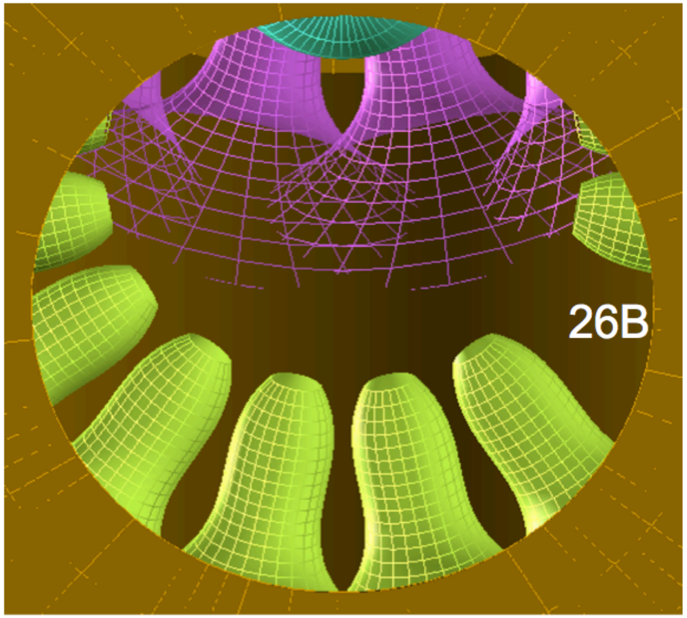
- Quantitatively assess impact of viscosity on ignition: devise test of simulations
- Understand limits of mass diffusive flux expression especially for strong shocks
  - Impact on energy transport, e.g., from LL: $q = [k_T(\partial\mu/\partial c)\big|_{P,T} - T(\partial\mu/\partial T)\big|_{P,c} + \mu]i - k\nabla T$
- Spallation from 1st shock in solid ablator: Design Omega experiment to test
- Design Hy-Eq Symcap platform to dial in kinetic effects
- Hot electron anisotropy could seed non-uniform burn: Quantify
- Assess upper bound on possible resistive heating in fuel
- Does enthalpy of mix contribute to low DSR?
- Hohlraum/gas interface mix from ion diffusion or hydro-instability: does it play a role on missing energy / multipliers?
- Local Kn physics in hot spot and effects on ion temperature measurements

The plasma bubbles correlate with the beam locations, and the instability features are near the root of the outer beams (courtesy of Hui Chen)

GLEH: N160202-004



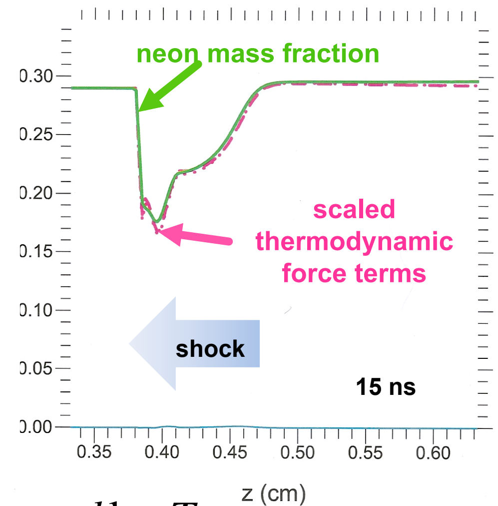
Visrad: N160202-004 (GLEH view)



Gold bubbles grow at 50um/ns to about 2 mm out of the hohlraum wall.

Nels Hoffman

Species separation in planar steady shock wave replicates thermodynamic force terms, if Péclet number is large



- Planar steady shock wave in binary mixture
- Solution to continuity equation for mass fraction c of light species

$$c(x) \cong c_+ + \frac{F(x)L_i}{R_+(x)Pe(x)} - \sum_{n=1}^{\infty} \frac{L_i^{n+1}}{\left[-R_+(x)Pe(x)\right]^{n+1}} \frac{d^n F(x)}{dx^n}$$

where

c_+ = mass fraction in unshocked material

$F(x)$ is thermodynamic force:

$$F(x) = k_P(c(x))\frac{d\log P_i}{dx} + k_E(c(x))\frac{T_e}{T_i}\frac{d\log\rho}{dx} + k_T^{(i)}(c(x))\frac{d\log T_i}{dx} + k_T^{(e)}(c(x))\frac{d\log T_e}{dx}$$

$Pe(x)$ is Péclet number: $Pe(x) = u_+ L_i / D(x)$, where u_+ is shock velocity, L_i is shock width,

$D(x)$ is diffusivity, $R_+(x)$ is (compression)$^{-1}$ = $\rho_+/\rho(x)$

- When Pe is large,

$$c(x) \approx c_+ + \frac{F(x)L_i}{R_+(x)Pe(x)}$$

Expression is suggested by solution to approximate linear ODE with constant coefficients

C. Orth preliminary proposal — Add phase nucleation & spallation to target design codes

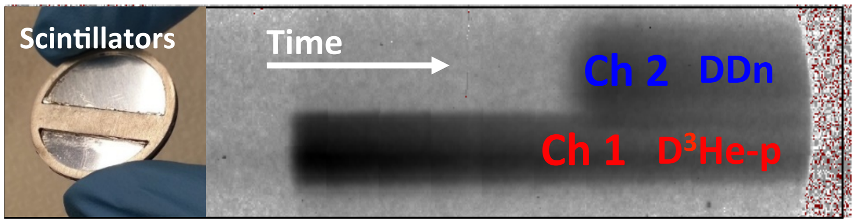
- When a ≥1 Mbar-level shock transits ablator material still in a solid phase (e.g., as determined by its temperature or MJ/kg), keep it in the solid phase for another Δt ps (e.g., don't let it expand). — This is secondary.
  - Work with Orth to determine Δt (~200 ps?).

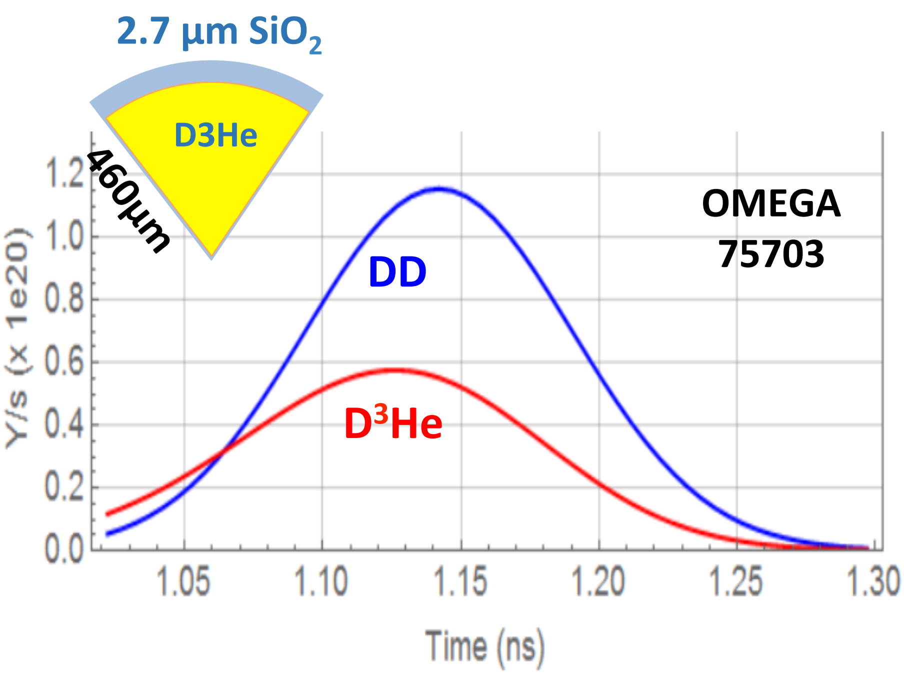
- If the shock transit of a solid region is adjacent to the fuel, make the solid spall according to the following reference, delay the shock propagating further by Δt ps, and roughen the surface according to the expected size of the spalled chunks (1, 10, and 14 microns respectively for HDC, sintered Be, and GDP-CH).
  - This is primary (and not easy).
  - C. Orth, Physics of Plasmas, **23**, 022706-1 (2016).

04/07/2016

High-precision measurements of multiple nuclear burn histories to probe time evolution of species separation in kinetic to hydro-like 1D plasmas

PXTD streak image of DD and D^3He signal



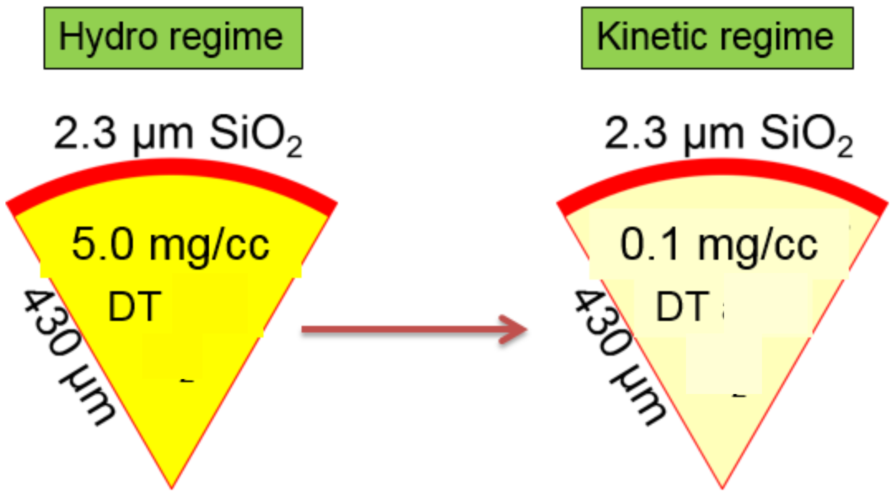


Additional measurements:

- Yield(DD) and Yield(D^3He)
- Tion(DD) and Tion(D^3He)
- Te
- DD and D^3He burn profiles
- R(t)
- Convergence
- ρR_{fuel} and ρR_{tot}
- ....
- ....

Physics motivation:
To quantify the instantaneous rate of species separation in implosions

DT exploding pushers at OMEGA will be used to explore the transition between hydro/multi-fluid to kinetic regimes



$\lambda_{ii} << R_{fuel}$
N_K ~0.01
(at bang time)

$\lambda_{ii} >> R_{fuel}$
N_K ~10
(at bang time)

D fraction varied: 20,50, 80, 100%

Measured quantities on one DT shot:

Yield (DD) and Yield (DT)
Tion(DD) and Tion(DT)
Te
DT and DT burn histories
DT and DD burn profiles
R(t)
Convergence
ρR_{fuel} and ρR_{shell}
....
....

PHYSICS MOTIVATION:
Simplest possible implosions with extensive precision diagnostics, **leaving no wiggle room**, that can be compared in detail to fluid, hybrid, and kinetic simulations.

RELEVANCE:, hot-spot ignition (shock convergence), wetted foam, shock ignition, species separation, species temperature disequilibrium, ….

Recent work is assessing enthalpy of mixing in HDC implosions and gas-filled hohlraums

ENTHALPY OF MIX

- Temperature and pressure differences between two contiguous vessels with distinguishable particles drives enthalpy change (*H*=*E*+*PV*)

$$\Delta H = Nk_B T' \ln\left[\left(\frac{P_1}{P'}\left(\frac{T'}{T_1}\right)^{c_P/k_B}\right)^{c} \cdot \left(\frac{P_2}{P'}\left(\frac{T'}{T_2}\right)^{c_P/k_B}\right)^{1-c}\right], \quad \text{where}$$

$$\frac{1}{P'} = \left[\frac{cT_1}{P_1} + \frac{(1-c)T_2}{P_2}\right] \cdot \frac{1}{cT_1 + (1-c)T_2}, \qquad T' = \frac{N_1 T_1 + N_2 T_2}{N_1 + N_2},$$

- Pressure gradient scale length often well exceeds temperature gradient scale length, leading to isobaric approximation

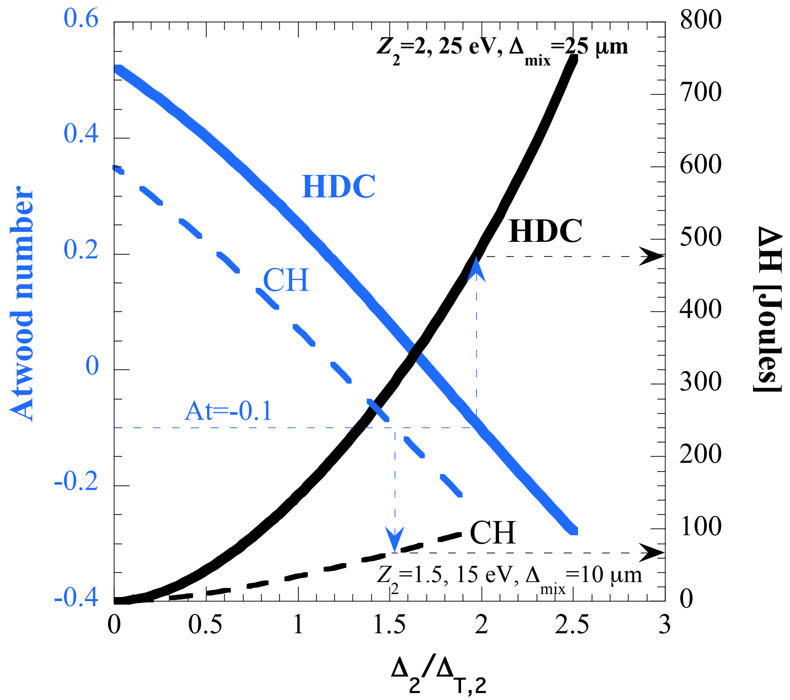
  - $\Delta H = \Delta Q$ and $\Delta E = \Delta H - P dV$

Recent work is assessing enthalpy of mixing in HDC implosions and finds potential several hundred J of ΔH

ENTHALPY OF MIX

- Under quasi-isobaric conditions we can solve for the Atwood number on the DT ice/pusher interface for a parameterized temperature ratio

$$At = \frac{\frac{A_2}{1+Z_2} - \frac{A_1}{1+Z_1}\cdot\left(\frac{T_2}{T_1}\right)}{\frac{A_2}{1+Z_2} + \frac{A_1}{1+Z_1}\cdot\left(\frac{T_2}{T_1}\right)} \qquad \frac{T_2}{T_1} \cong \frac{1+\frac{\Delta_2}{2\Delta_{T,2}}}{1-\frac{\Delta_1}{2\Delta_{T,1}}}$$



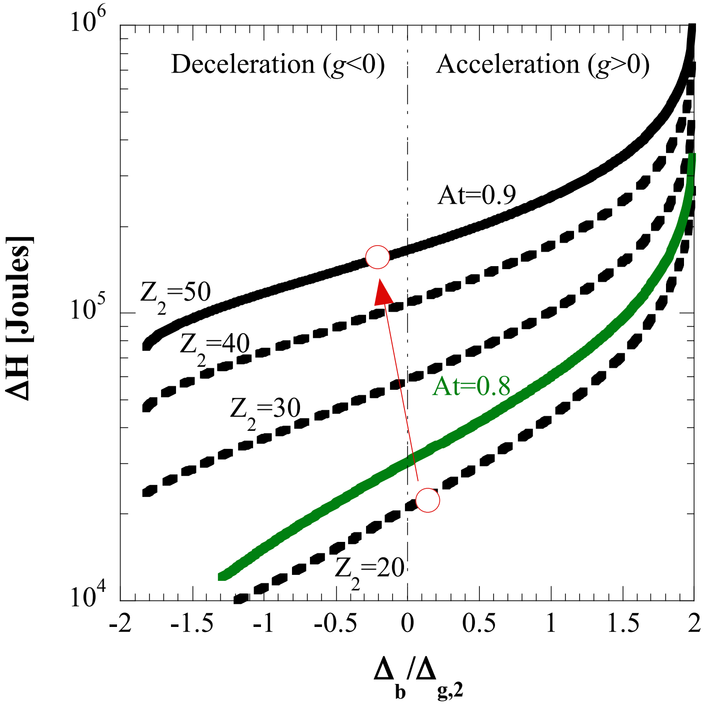
- For a temperature ratio free of resonance at $\Delta_1=2\Delta_{T,1}$, e.g., (1+tanh)/(1-tanh), ΔH for HDC is ~ 200 J

Recent work is assessing enthalpy of mixing in gas-filled hohlraums and finds nearly 100 kJ of ΔH

ENTHALPY OF MIX

- For given normalized bubble size and Atwood number, ratio of temperatures is used to evaluate DH

$$\frac{T_2}{T_1} = \frac{\left[1 + \frac{2\Delta_b}{\Delta_{g,2}}\left(\frac{1-At}{1+At}\right)^{0.66}\left(1 - \frac{\Delta_b}{2\Delta_{g,2}}\right)\right]^{1/2} - 1}{\frac{\Delta_b}{\Delta_{g,2}}\left(\frac{1+At}{1-At}\right)^{0.34}\frac{1+Z_2}{1+Z_1}\frac{A_1}{A_2}}.$$



- ΔH between end of low foot to peak power exceeds 100 kJ for Z_{Au}=50, At=0.9

Currents are generated in converging shocks in ICF fuels, leading to Joule heating not captured in mainline codes

JOULE HEATING

- Shock front electric field E scales as: $E \cong k_B T / e\Delta_s \equiv k_B T / e\eta_\infty \lambda_{mfp}$

- Ion mean free path scales as T^2/n, giving: $E \cong k_B T / e\eta_\infty \lambda_{mfp} \propto n / T$

  - Converging shocks in fuel reach Mach number near 50, so that $E \to 0$ near center at shock flash

  - Consequently, *E* is strong function of time during shock transit

- Ampere's Law gives: $\int dV \int dt\ \vec{j} \cdot \vec{E} \cong -\int dV \int dt \cdot \partial_t E^2 / 8\pi \equiv V \left\langle E^2 / 8\pi \right\rangle_{Volume}$

Currents are generated in converging shocks in ICF fuels, leading to Joule heating not captured in mainline codes

JOULE HEATING

- For Rev.5 CH design (4 shocks):

$$\left\langle \frac{E^2}{8\pi} \right\rangle [erg/cm^3] = \frac{118 \cdot 16^4 \rho_0^2 [mg/cm^3] \ln^2 \Lambda}{T_e^2 [keV] \eta_\infty^2},$$

- Using ρ_0=0.4 mg/cm^3, lnΛ=10, $\bar{T}_e$=0.1 keV, V=0.002 cm^3, we find several Joules of resistive heating in gaseous fuel

- Increase in fuel pressure at deceleration onset leads to decrease in stagnation pressure of ~30-40% from adiabatic implosion model

Electron and ion thermo-diffusion may be greatly enhanced in high-*Z* hohlraums filled with low-*Z* gas

HOHLRAUM DIFFUSION

$$i = -\rho D \cdot (\nabla\alpha + k_P \nabla \ln P + k_{T_e} \nabla \ln T_e + k_{T_i} \nabla \ln T_i + \ldots)$$

Kagan and Tang, Phys. Lett. **A 378**, 1531 (2014)

$$\nabla \ln T = \nabla \ln P \left(\frac{\gamma - 1}{\gamma}\right) + \frac{\Delta Z}{\bar{Z} + \Gamma^{-1}} \frac{m_1}{m_2} \times \frac{\nabla\alpha}{[\alpha + (1-\alpha)m_1/m_2]^2},$$

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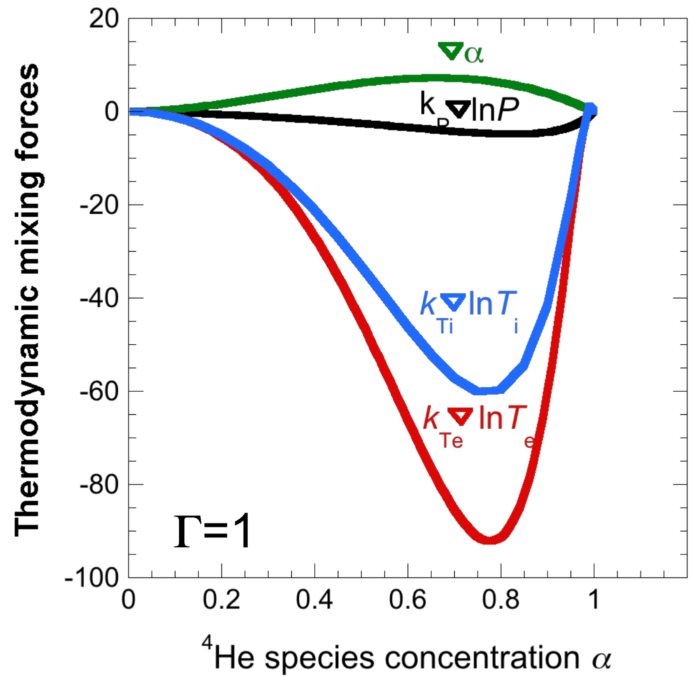

- Large ΔZ can promote temperature inversion within mix layer, potentially leading to throttled e$^-$ transport and reduced drive